

Nanometer Imaging with a High Brightness Source

August 22nd , 2003

X-Ray Science with Coherent Radiation



Topics

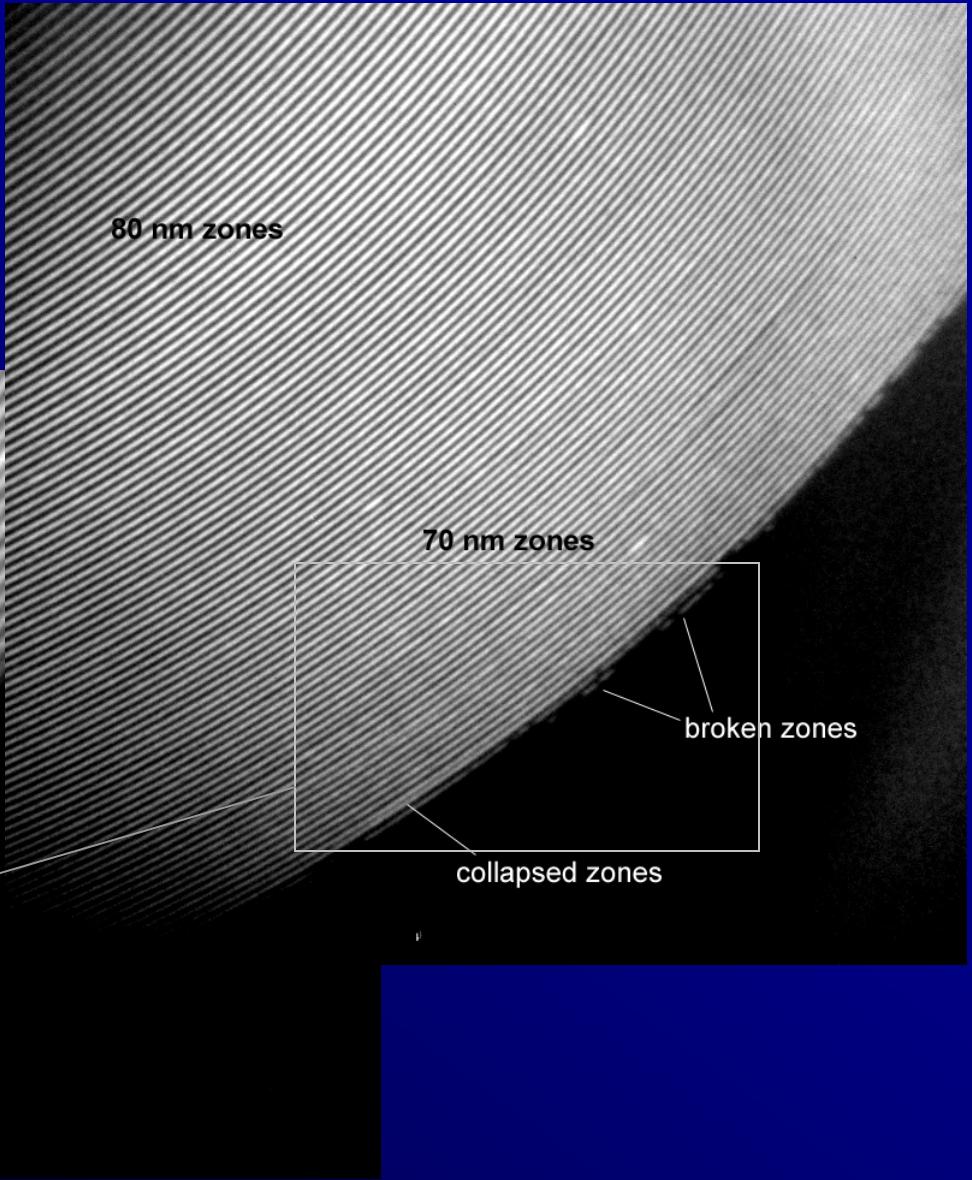
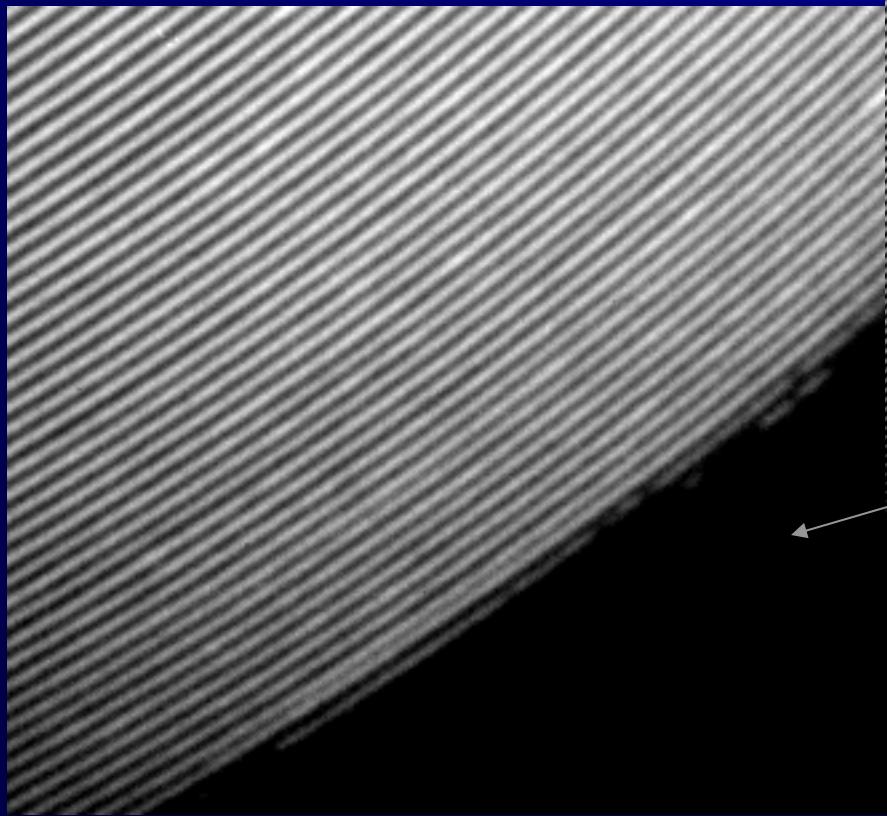
- Key parameters of an imaging system
- Advantages of x-ray imaging
- X-ray imaging performance with a laboratory source
- Exposure time and high brightness advantage
- Focusing optic for nanometer resolution?

Key Parameters of a Microscope

- Resolution
- Contrast and exposure time
- Depth of focus, important for 3D tomography

Image of a Zone Plate Acquired with the TXM

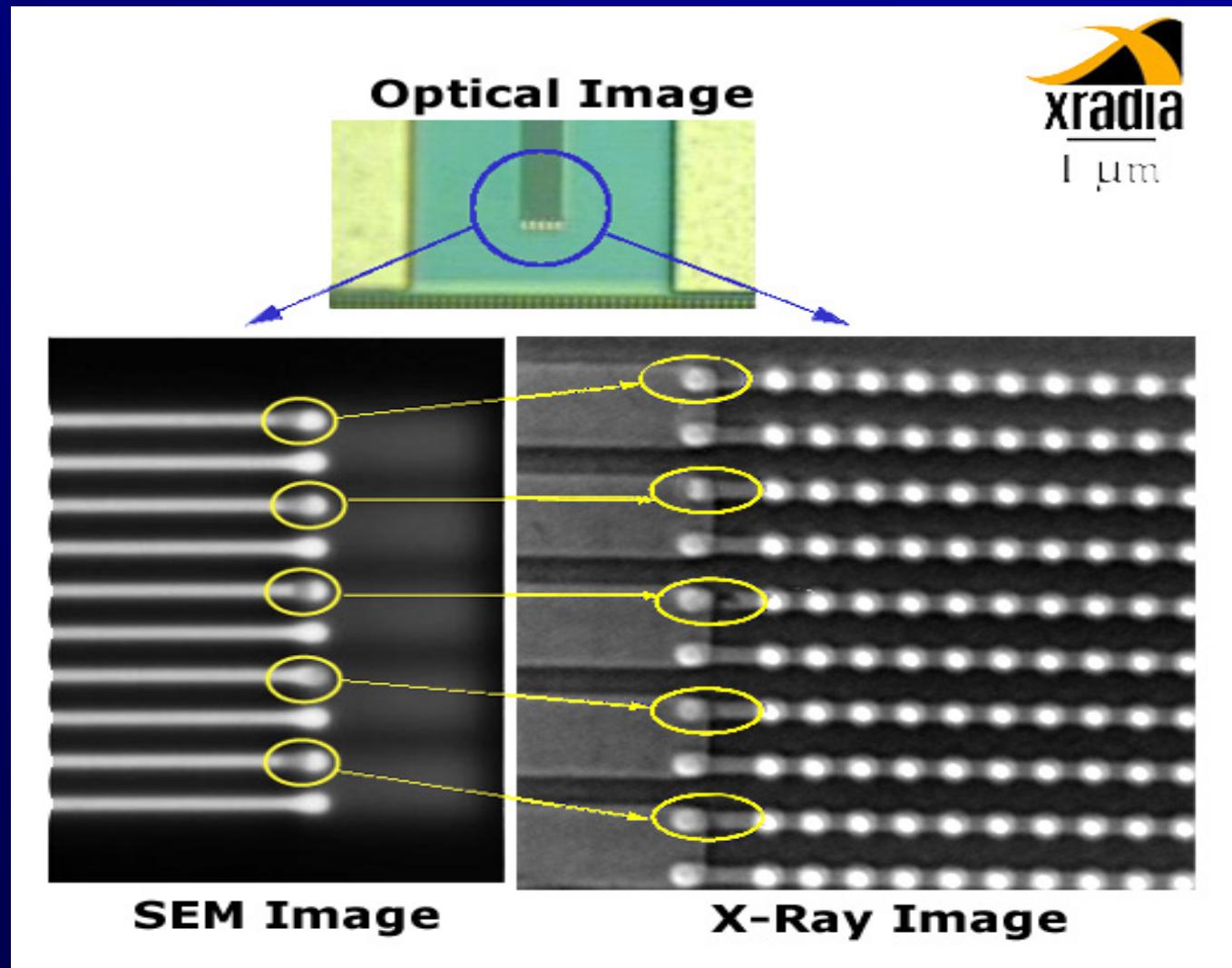
A gold Fresnel zone plate imaged with the TXM. The 70 nm outer zones are clearly resolved, along with defects in the zone plate.



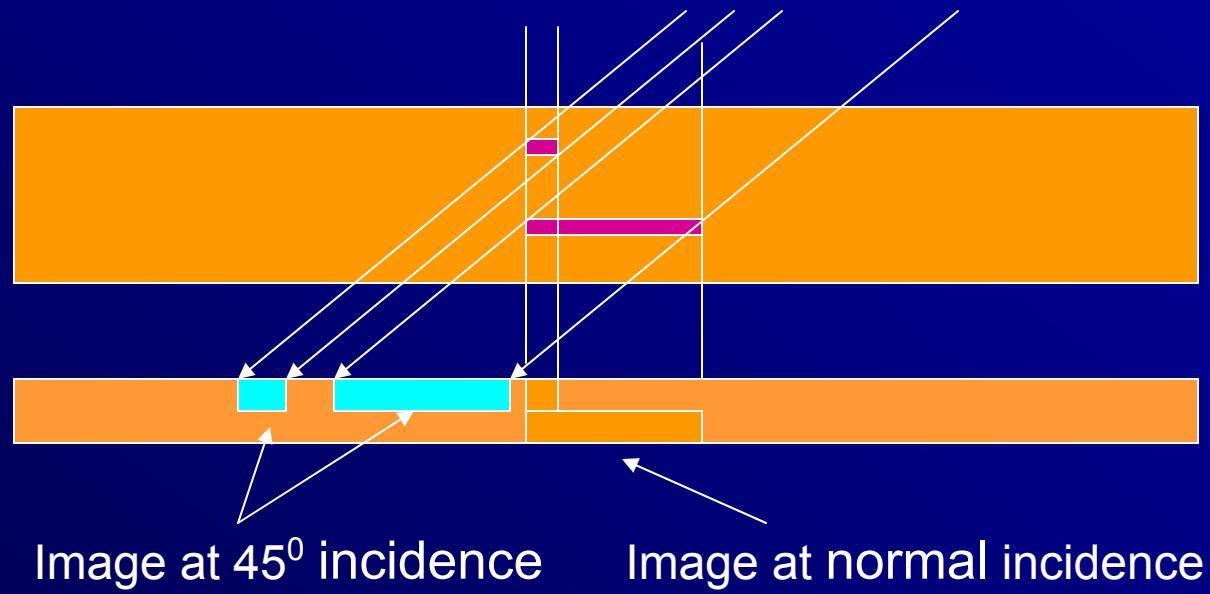
Advantages of X-ray Imaging

- Short wavelength for high resolution
- High penetration for nondestructive imaging
- Adding spatial resolving power to well-established x-ray techniques, e.g., x-ray spectroscopy and diffraction

The X-ray Advantages: High resolution+3D information

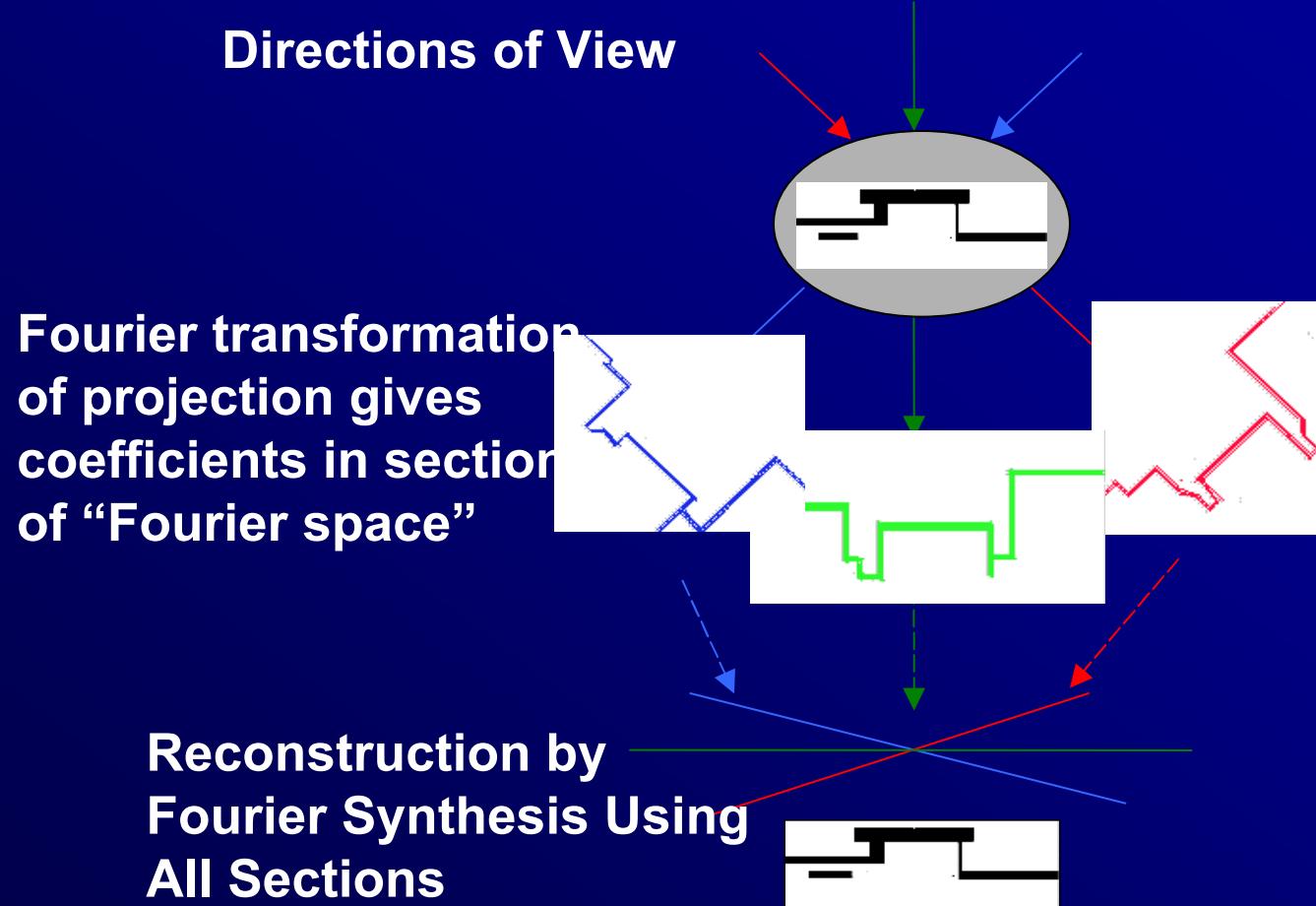


3D Tomography Basis

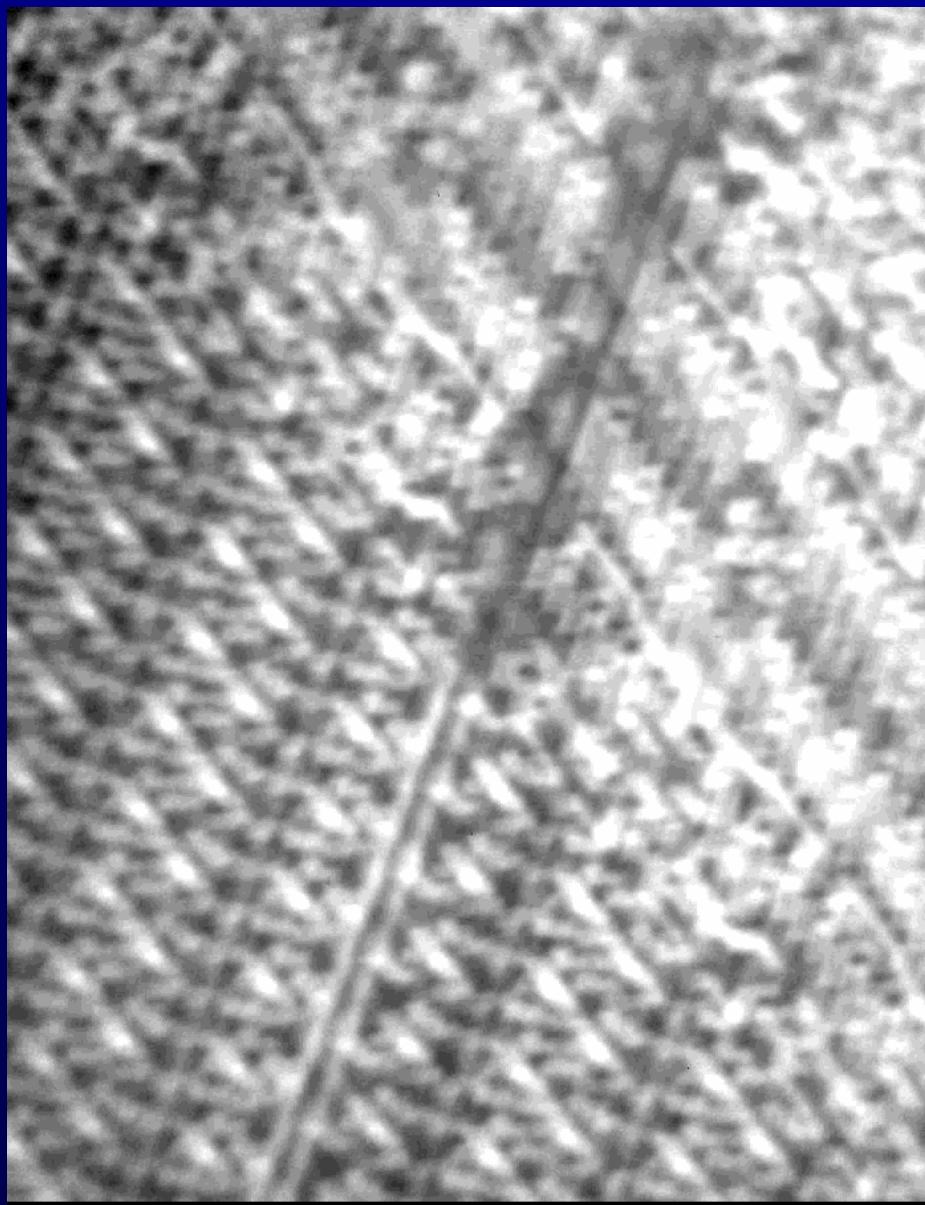


Structures at different depths result in lateral separation when rotated.

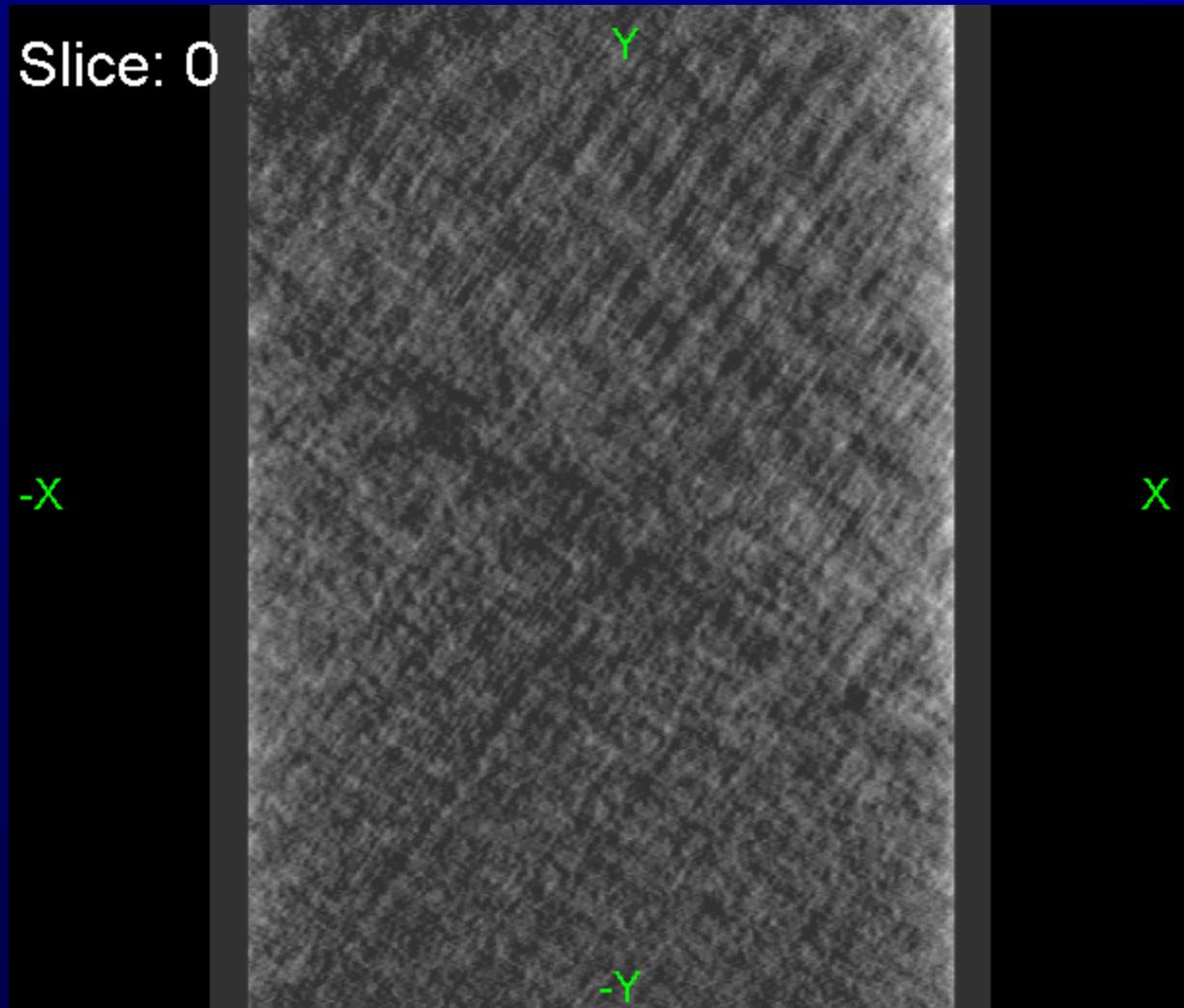
Schematic Representation of the Tomography Principle



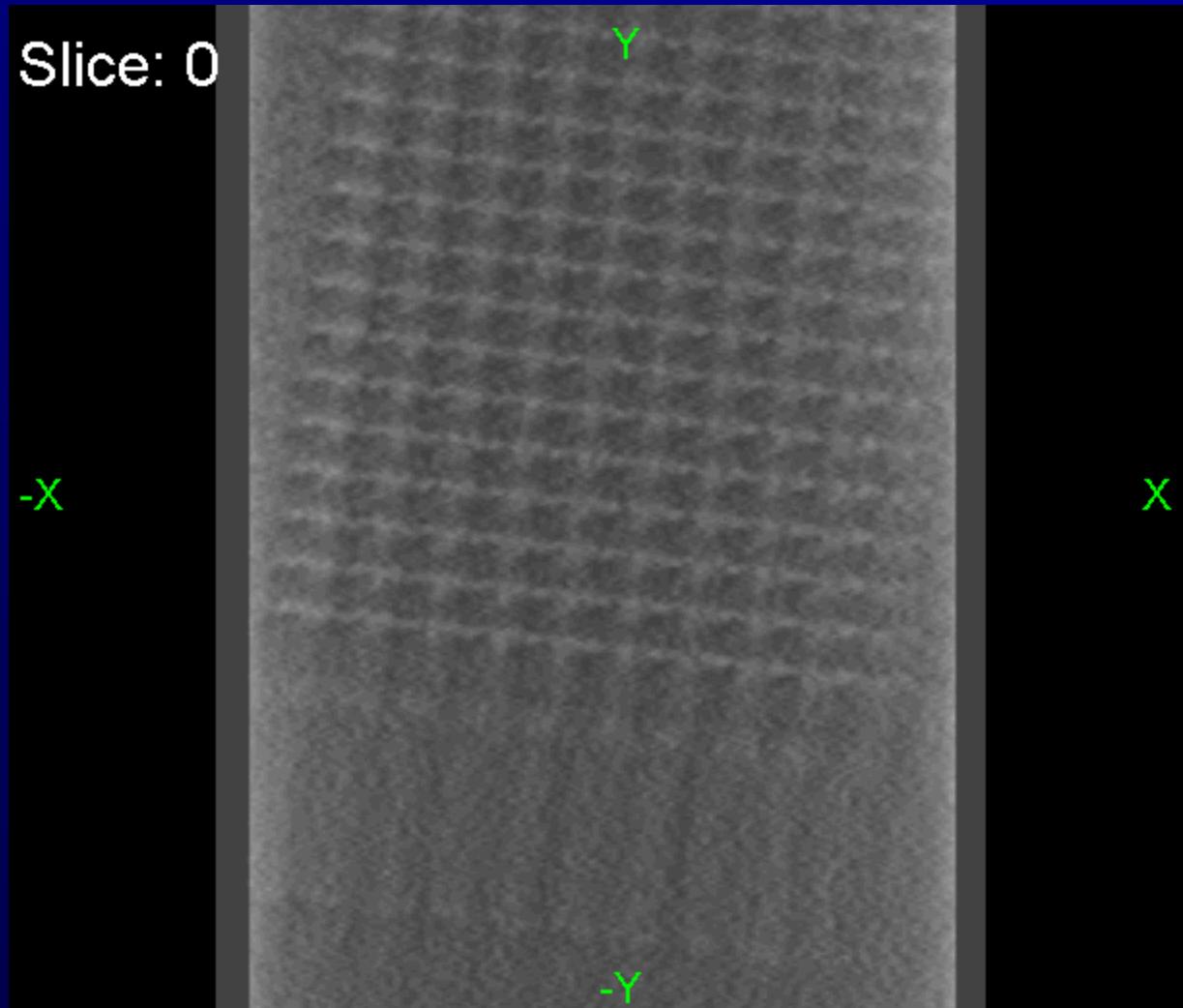
Area B Projections –60 degrees to +60 degrees



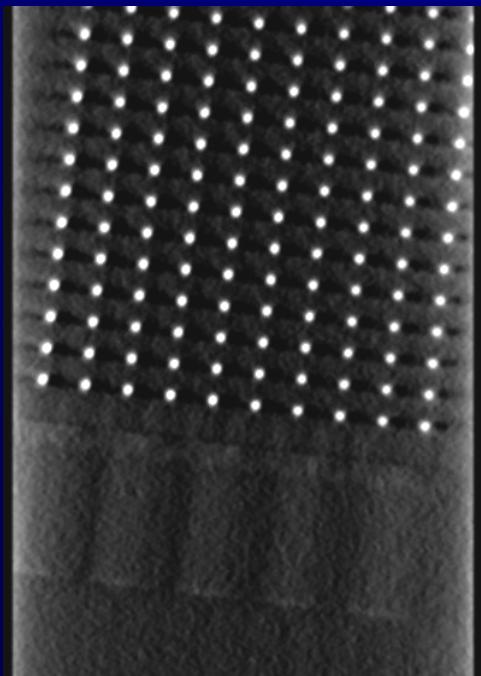
Area B Reconstruction – slices through the XY planes showing the metal layers



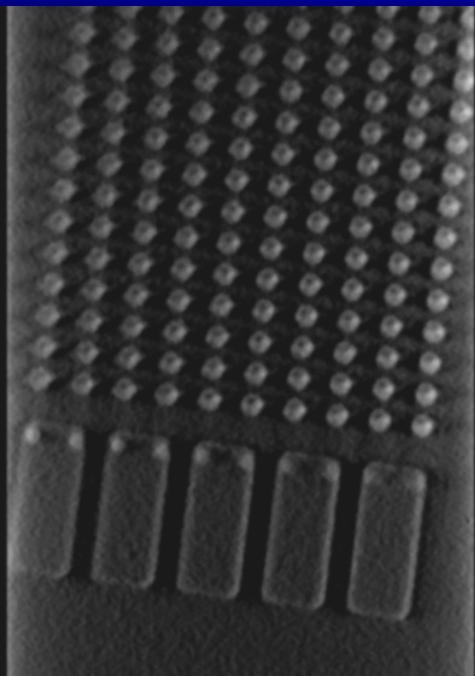
Electromigration Sample Reconstruction



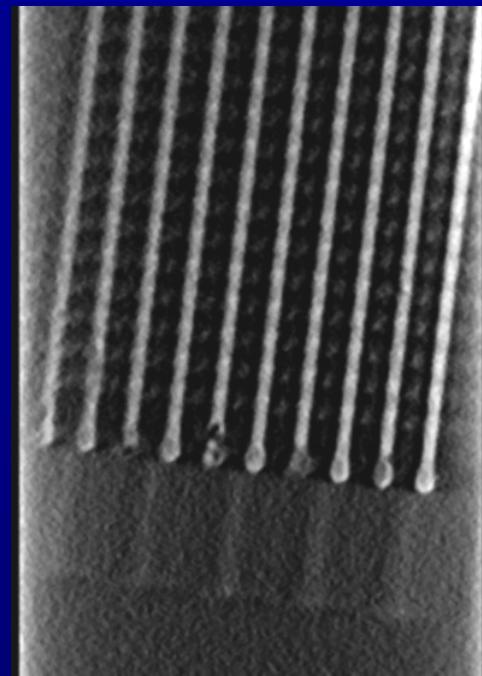
Reconstruction Slices



Heat sink layer

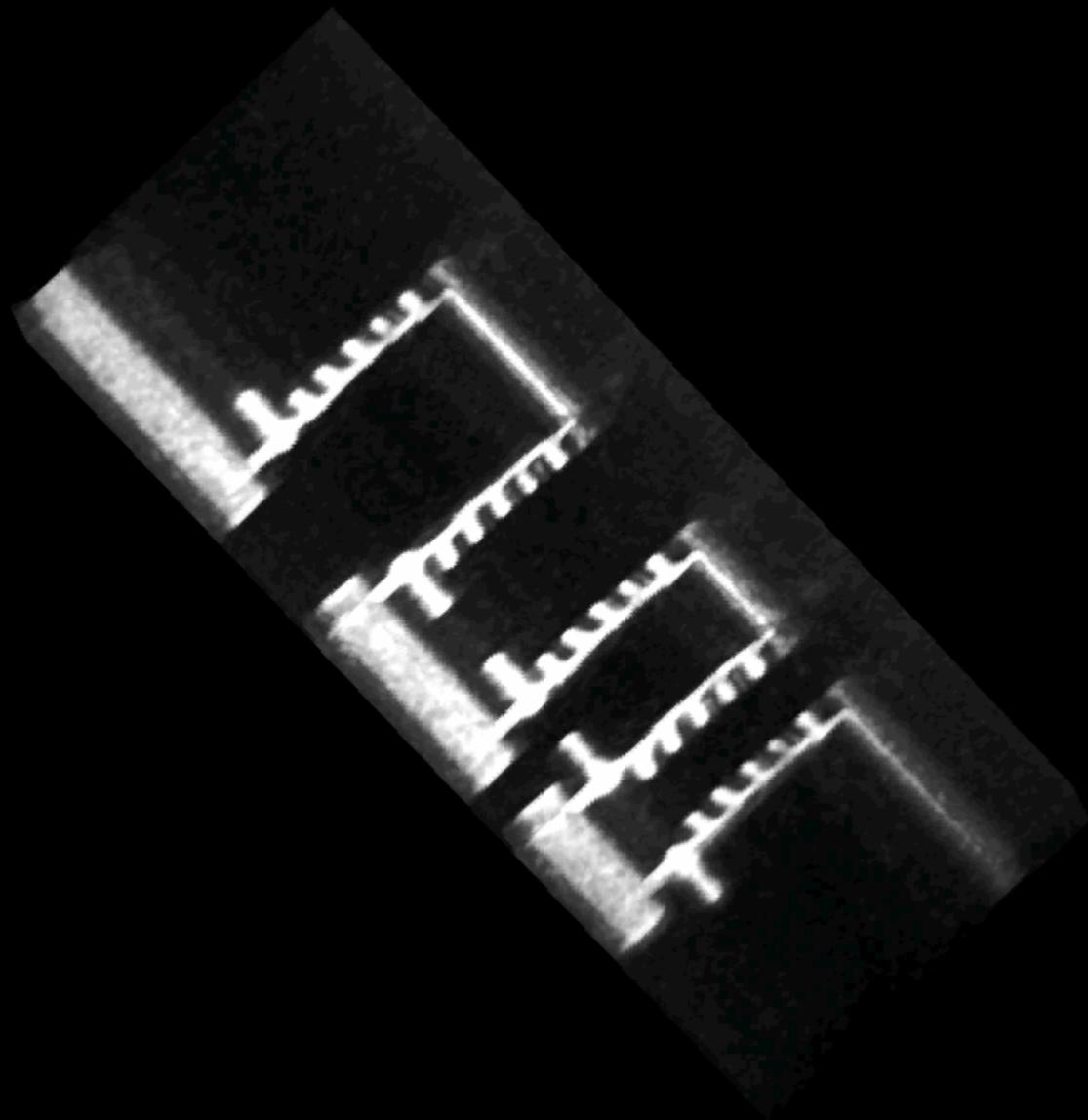


Pad layer



Line layer

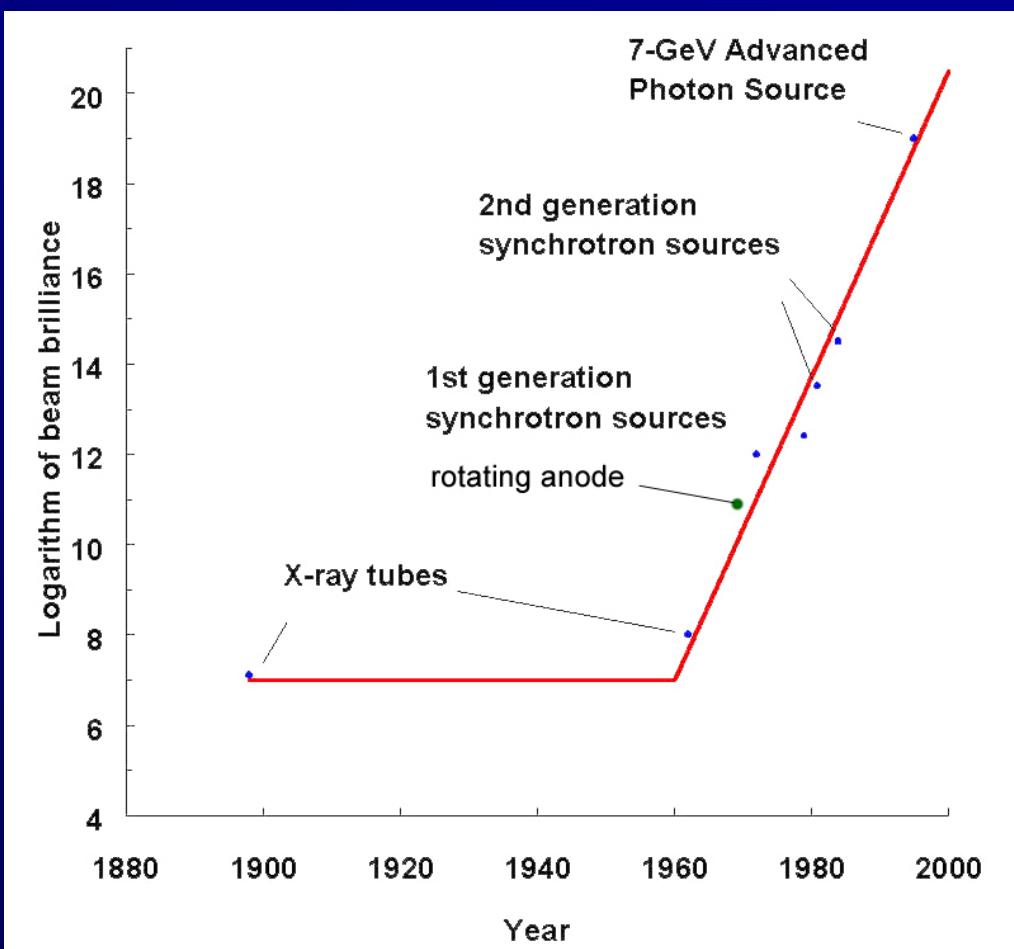
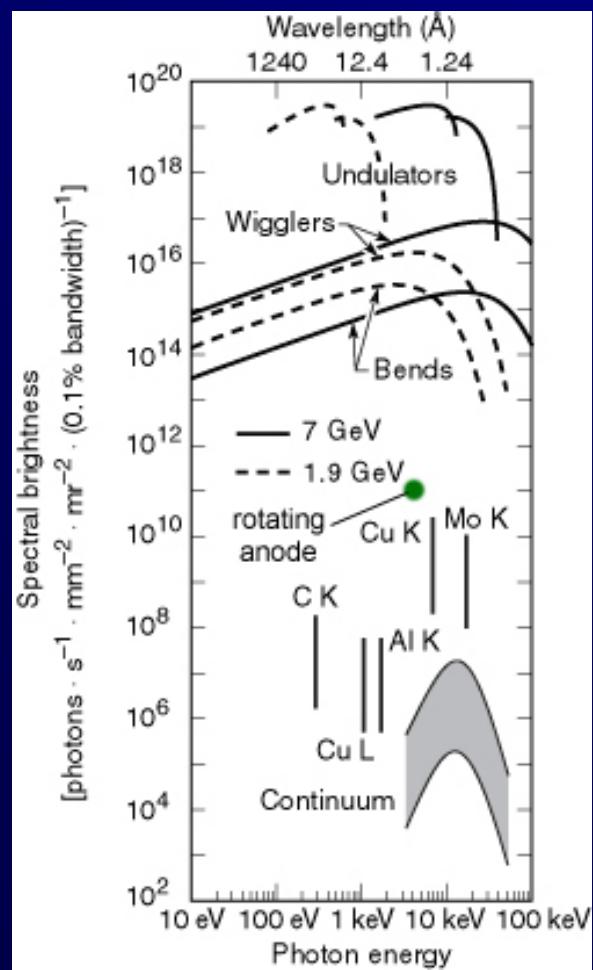
A Rendered 3D Image of a 8-level Cu Device Showing Electromigration Defects



System Components – X-ray Source

X-ray source of
TXM 54-80:

A commercial rotating anode source from Rigaku
with Cr anode - 5.4 keV x rays from Cr $K\alpha$ -line.



Scaling of Exposure Time T with Resolution δ

- $T \sim 1/\delta^4$ for imaging without a lens objective
 - $1/\delta^2$ due to the reduction of pixel area
 - $1/\delta^2$ due to the reduction of thickness and thus contrast
- $T \sim 1/\delta^2$ for imaging with a lens objective
 - An improvement of δ^2 due to an increase of illumination beam convergence

Resolution (nm)	600	60	6
Scaling factor without an objective	1	10^4	10^8
Scaling factor with a lens objective	1	10^2	10^4

Source Brightness Advantage

- $T \sim 1/B$ $B = \text{Average source brightness}$

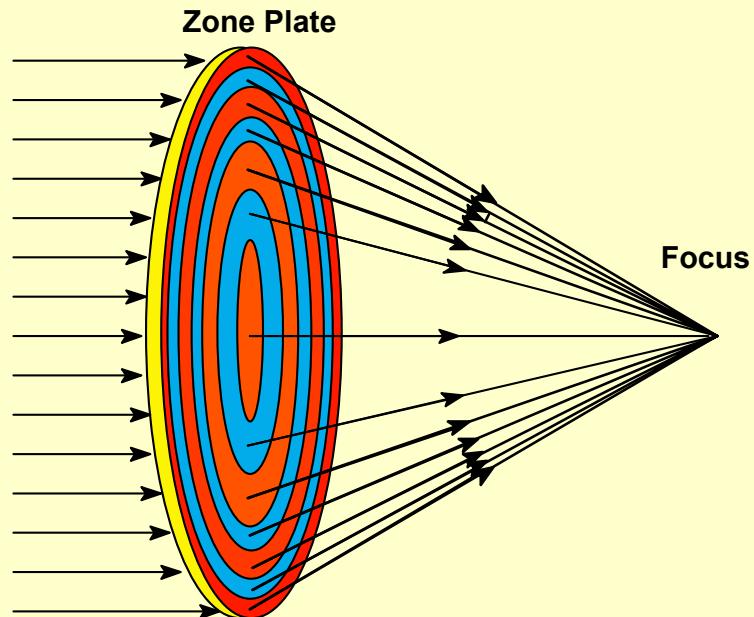
Source	Normalized B	T @ $\delta = 60\text{-nm}$
Rotating anode	1	600 sec
Bending magnet	10^4	100 msec
Undulator	10^8	$10 \mu\text{sec}$
4 th generation	$>10^{10}$	Single pulse?

X-ray imaging with resolution better than 6 nm should be possible with even a bending magnet source with an exposure time of about 100 sec

Performance Comparison of X-ray Focusing Optics

	KB Mirror	Refractive Lens	Zone Plate
Resolution (nm)	100	100	20 for 0.5 keV 60 for 4-15 keV
Flux Density Gain	>300,000	~300	>300,000
Coherence preservation	Acceptable ?	Acceptable?	Good
Imaging Optic	No	Yes	Yes
Chromatic Aberration	No	$1/\lambda^2$	$1/\lambda$
Theoretical resolution limit (nm)	<10	60	<10

Zone Plate Basics



Equation

$$R_k = (kf\lambda)^{1/2}$$

f = focal length

k = zone index

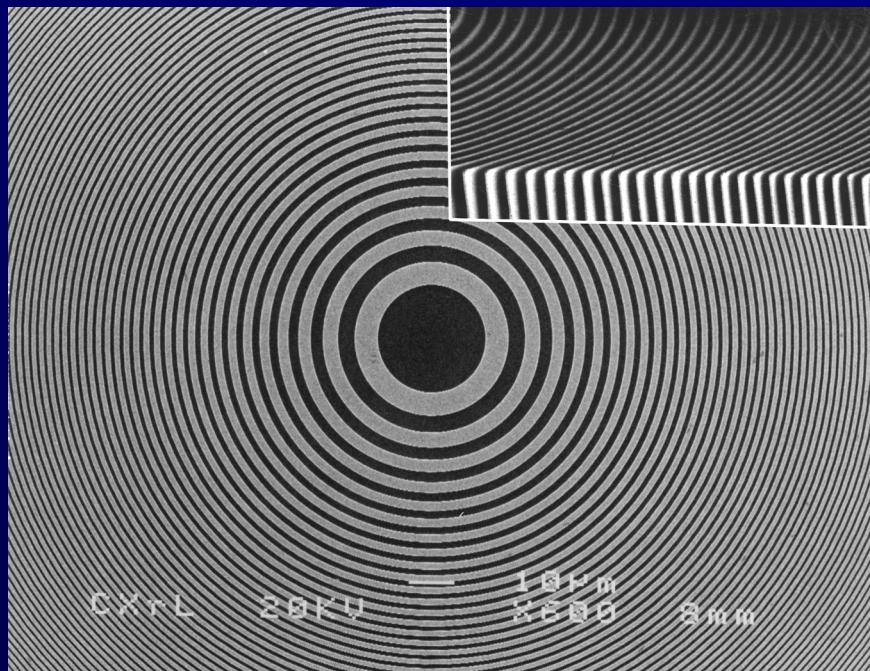
λ = wavelength

Resolution

Amplitude Object: $\delta = 1.22\Delta R_k$

Zone Plate's Key Parameters

Zone plate consists of concentric rings (zones) with zone width decreasing with radius



Key parameters:

Number of zones

> 100 required for good focusing

Outermost (smallest) zone width

Determines resolution and NA

Zone materials, thickness, profile

Focusing efficiency

Focal length

Working distance

SEM Image of a ZP and its zone profile

Challenges of Zone Plate Fabrication

Precise high aspect ratio nanostructuring in high mass density materials, e.g. Au



Aspect ratio (AR) required for optimal focusing efficiency of 5.4 keV x-rays in an Au zone plate

Resolution (nm)	100	80	60	30
Optimal AR	9	13	17	33

~ 8.4 times larger aspect ratio is required for Si zone plates

← Grating structure with an aspect ratio of 30

Highest Performance Zone Plates Produced for X-ray Applications

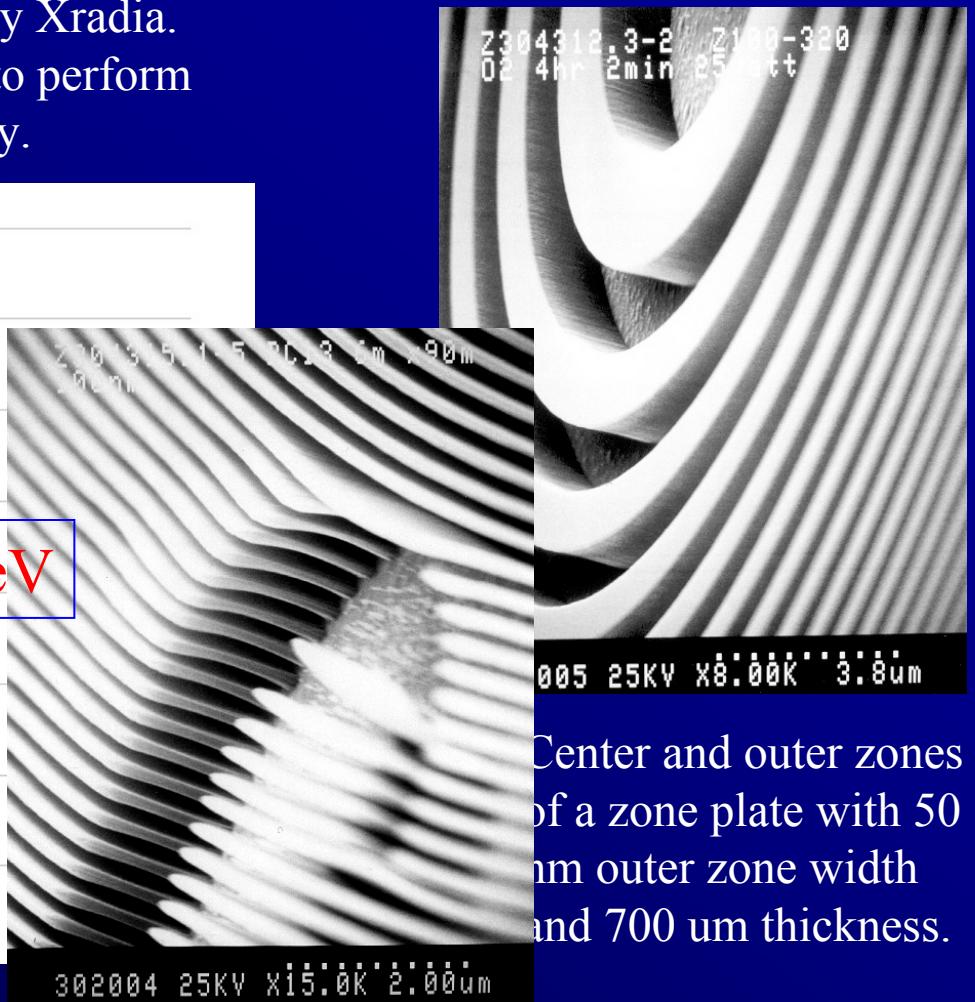
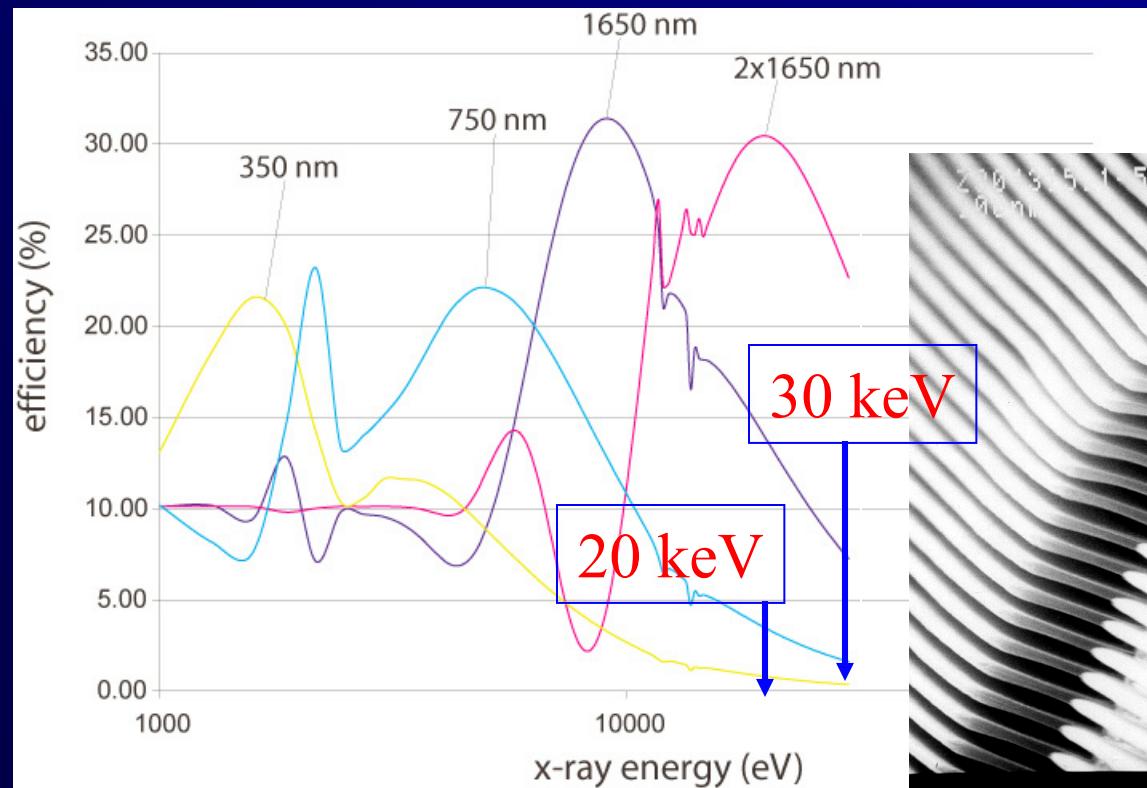
Energy (eV)	Outermost Zone width (nm)	AR	Efficiency (%)	Diameter (μm)	Material
~500	20	8	16	60	Ni
4000	50	8	8	50	Au
5400*	50	15	17	80	Au
5400*	70	11	17	80	Au
9000	100	16	31	160	Au

Xradia is currently developing zone plates with finer zones and large diameters



Zone plates fabricated at Xradia

Theoretical efficiency of zone plates made by Xradia.
Zone plates made by Xradia are guaranteed to perform
with at least 75% of the theoretical efficiency.



Center and outer zones
of a zone plate with 50
nm outer zone width
and 700 um thickness.

Zone Plate Material Selection

- High ρ to reduce aspect ratio requirement
- High α/β ratio to increase efficiency, e.g., select element having an absorption edge higher than the high end of the design energy range
- Manufacturability of a selected material, e.g., Au, Ni, Ta, and Si

Note: High Z materials are generally preferred for hard x-ray applications

Depth of Focus (DOF)

- $\text{DOF} \sim 4\delta^2/\lambda$

DOF increases linearly with x-ray energy E

	E=500 eV	E = 5000eV
D = 25 nm	1 μm	10 μm
50	4	40
75	9	90

Path to sub 10-nm x-ray imaging

- Improving zone plate fabrication technology
- Using higher order diffraction m

$$\delta = 1.2 \Delta R/m \quad \Delta R = \text{the outermost zone width}$$

Example: $\delta = 20 \text{ nm}$ for $\Delta R=50$ and $m = 3$

$= 12 \text{ nm}$ for $\Delta R=50$ and $m = 5$

Focusing efficiency $\sim 1/m^2$

- Allocating resources and collaborate with industry

Summary and Conclusions

1. 3D x-ray tomographic imaging using multikeV x-rays has been demonstrated with a laboratory source with 70-nm resolution.
2. High brightness synchrotron sources, especially 4th generation sources, will allow sub-10 nm resolution and exposure time with a single pulse.
3. Zone plates with a 60-nm resolution has been developed for multikeV x-rays.
4. Imaging with 12-nm spatial resolution may be demonstrated with the currently available zone plates at the expense of reduced focusing efficiency
5. Fabricating zone plate with sub-10 nm resolution and adequate focusing efficiency requires substantial technical development.